Space Missions Trade Space Generation and Assessment using the JPL Rapid Mission Architecture (RMA) Team Approach

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Abstract—The JPL Rapid Mission Architecture (RMA) capability is a novel collaborative team-based approach to generate new mission architectures, explore broad trade space options, and conduct architecture-level analyses. RMA studies address feasibility and identify best candidates to proceed to further detailed design studies. Development of RMA first began at JPL in 2007 and has evolved to address the need for rapid, effective early mission architectural development and trade space exploration as a precursor to traditional point design evaluations. The RMA approach integrates a small team of architecture-level experts (typically 6-10 people) to generate and explore a wide-ranging trade space of mission architectures driven by the mission science (or technology) objectives. Group brainstorming and trade space analyses are conducted at a higher level of assessment across multiple mission architectures and systems to enable rapid assessment of a set of diverse, innovative concepts. This paper describes the overall JPL RMA team, process, and high-level approach. Some illustrative results from previous JPL RMA studies are discussed. [1] [2]

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1. INTRODUCTION

Development of RMA began at JPL in 2007, and it has grown to become an important new part of the evolved JPL "Team X" set of services for mission formulation phase advanced design studies [1] [2] [3]. RMA was developed to address the need for rapid, effective early mission architectural development and trade space exploration as a precursor to the traditional "point design" development stage, e.g., dedicated mission proposal teams and the well-established JPL "Team X" point design team [4]. RMA provides concept creation, trade studies, feasibility assessment, and preliminary analyses prior to the selection of a specific point design for detailed study. The approaches described in this paper are from the JPL RMA "broad trade space study" type. Key figures of merit such as science value, cost, risk, and performance/resource estimates are evaluated across multiple mission architectures to identify the most promising options for further consideration. The RMA approach includes identifying innovative, unforeseen paths in the trade space. By rapidly examining a large number of varied mission and spacecraft options early, the RMA approach avoids a typical design team's natural tendency to drive to a baseline architecture prematurely and seeks to avoid getting constrained early on by a mission that does not adequately address the science objectives or has unacceptable cost or risk.

2. RMA TEAM ROLES AND RESPONSIBILITIES

RMA integrates a small team of broad-thinking, multidisciplinary experts to generate and explore a wide-ranging trade space driven by the mission science (or technology) objectives. RMA emphasizes using a small collaborative team of typically 6-10 people to enhance team efficiency, agility, and creativity. RMA is first and foremost a team-based approach, and RMA is not merely a set of tools. The team members are one of the most important functional elements in RMA. RMA study teams are typically formulated with participants known for demonstrated abilities for broad, "system-level" thinking. Such a team often combines diverse backgrounds and experience from across the science, engineering, and technology communities.

RMA studies include a mix of the roles and responsibilities listed in Table 1. Specific roles are tailored depending on the needs of a particular study. Certain roles can be combined to reduce study cost when the study scope is sufficiently focused. Each participant has specific

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[2] IEEEAC paper # 1599, Version 3, Updated January 4, 2011

Table 1. Key RMA roles and responsibilities

RMA Role	Key Responsibilities
Customer Representative	Provide study scope and constraints. Provide RMA team with science background, objectives, and priorities. Participate in the group sessions to guide real-time decision making. Participate in and concur with science value assessment.
Architect	Lead the strategic scope of the trades, analyses, and architectures examined. Guide the team as executive decision maker.
Facilitator	Lead the team through the process to effectively manage progress in group sessions and quality of products. Promote the creative process and converge products.
Science	Act as an "honest broker" to translate between customer science objectives and the architectural implementations. Guide the team in science value assessment.
Instruments/Payloads	Characterize and suggest candidate payload suites for the science objectives and architectures.
Mission Design	Conduct trajectory, navigation, and ops concepts analyses and trades.
Systems Engineering (top-level)	Identify dead end paths and "tall tent poles," as well as relevant new opportunities (e.g., alternative system architectures, technology trades, etc.). Suggest modifications to architectures for practicality.
SE: Analysis	Lead the resource and performance analyses for the trade space options. Identify key analyses and perform preliminary assessments of system masses, telecom, and cost across multiple architectures.
SE: Risk	Identify, collect, and assess risks for the key trade space elements and multiple architectures.
SE: Integration	Support the specific analyses needed in collaboration with the SE Analyst. Capture in-session products. Generate and integrate intermediate products between sessions and final products.
Specialists or Technologists	Where specific needs arise, a study may include a specialist or technologist to address a particular key trade, feasibility issue, or risk.

responsibilities and products, but all participate in the creative and analysis processes across the architectural trade space. RMA study participants naturally interact and contribute ideas across many different parts of the trade space, as depicted in Fig. 1. Participants each have multidisciplinary skills that are exercised during the concurrent collaborative sessions. This contrasts with the collection of 20 or more individual focused discipline experts that typically form a classical Team X point design team.

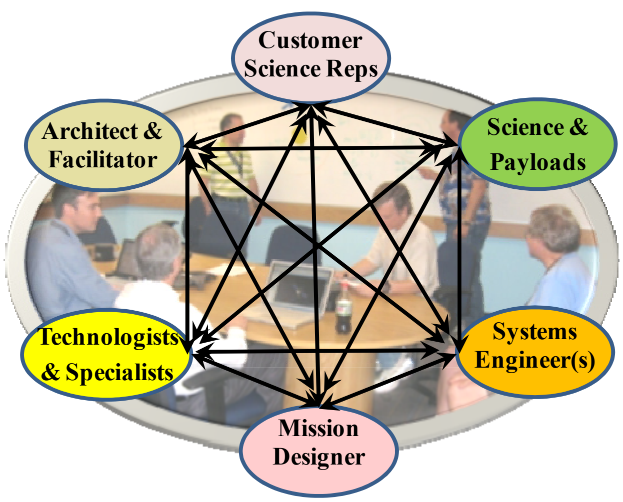

Figure 1. Small RMA team working in a concurrent setting enables efficient interactions and member contributions across the entire architectural trade space

Because the science objectives and priorities drive the study approach, concurrent participation by one or more representatives of the customer/science team is essential for real-time decision-making. These representatives participate throughout the entire study process and typically attend most of the concurrent group working sessions. The customer lead representative works closely with the study's Architect and Facilitator (sometimes a combined role), who guide the team and process during the study to ensure proper scope and timely convergence of the study and products.

3. Overview of the RMA Process and Approach

In the JPL RMA "broad trade space study" type, the approach involves rapid development and assessment of multiple innovative mission and spacecraft concepts for space science and technology missions. RMA combines the team and process to focus on identifying creative solutions across a wide-ranging trade space and quickly analyze multiple high-level trades and architectures. Dozens of potential mission options and combinations are winnowed down to 10 or more architectures that are assessed on a common basis before recommending best candidates for further study. By examining a large number of varied mission options early in the mission formulation stages, RMA avoids a typical design team's natural tendency to drive to a baseline architecture prematurely. This approach helps avoid getting constrained early on and spending significant study resources on a mission concept that does not adequately address the science objectives or has

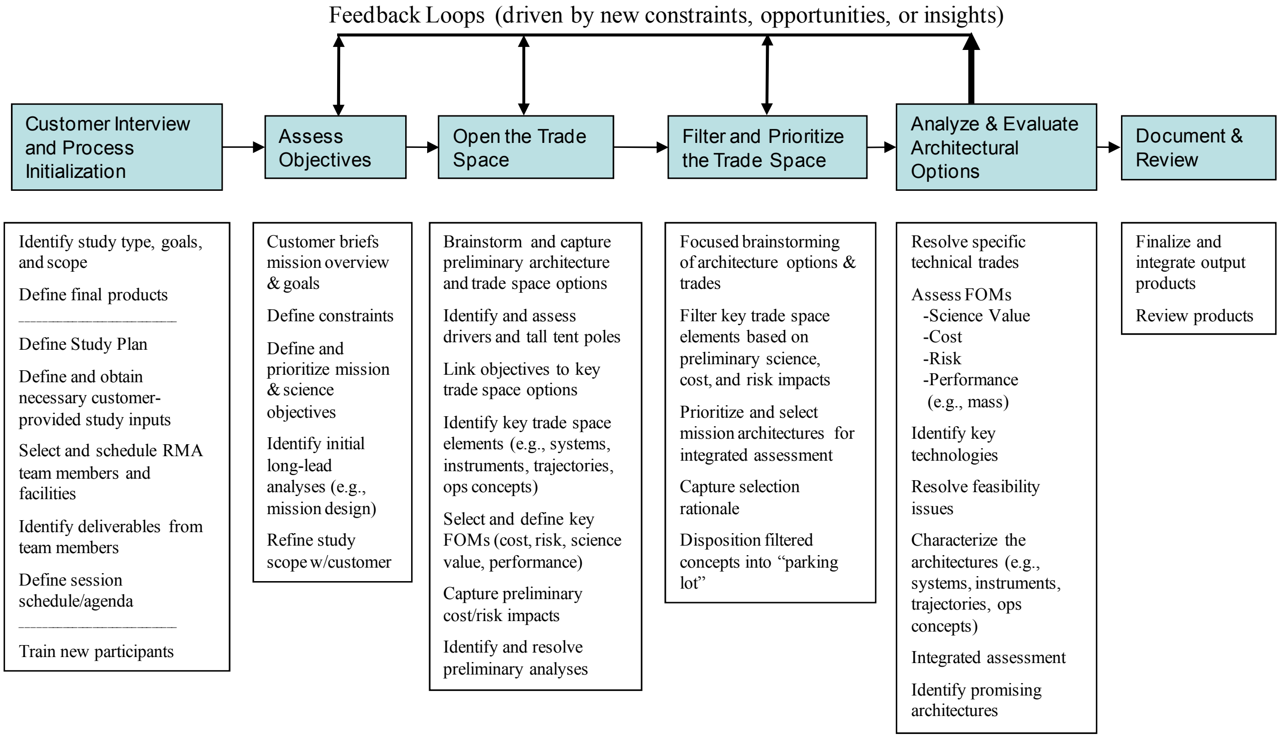

Figure 2. RMA process overview

unacceptable cost or risk. Diverse architectures are often generated spanning both conventional and novel systems, approaches, and technologies. A range of options including fly-bys, orbiters, landers, probes, and other architectural platforms may be considered and evaluated against the science objectives, cost, and risk. Generating this diverse set of options augments the focus of point design analysis teams and detailed proposal design teams (which evaluate a limited number of options in greater detail) by identifying the most promising architectures and elements of the trade space prior to the point design stage.

The RMA process operates on a rapid time scale to respond to short-turnaround customer needs. Collaborative group sessions are designed to span 1 to 3 weeks, depending on the scope of a study's trade space to be considered, and final products are generated shortly thereafter. Studies typically include 4 to 8 concurrent group working sessions of 2 to 3 hours each. Much of the work is done concurrently, but time is also allocated "offline" outside of sessions for research or certain analyses better suited for independent work. This approach enables much faster generation of results when compared to alternative trade space exploration approaches (particularly in the absence of pre-existing point designs) that take months of setup, preparation, analyses, reconciliation of results, and product generation. Often, such historical approaches suffer from inefficiencies due to their use of larger teams or much more detailed analysis approaches that are neither necessary nor appropriate for this early stage of trade space exploration.

The general RMA process is illustrated in Fig. 2. This process is flexible and adapted to specific study needs. It is not a scripted procedure. Depending on the extent of the trade space and analyses for a particularly study, each process stage can be modified as necessary to span only part of a group session or multiple sessions. Multiple mission architectures are assessed simultaneously throughout the process to enhance efficiency and stimulate sharing of ideas between architecture types. This approach is in contrast to a process that simply evaluates a set of point designs one at a time in series, which is more prone to inefficiencies and inconsistencies in the assessments. In addition, feedback loops in the process provide opportunities to examine new ideas at various stages. Intermediate products are captured both real-time during sessions and outside of sessions, and these products evolve between stages as the study progresses. Impacts to the primary figures of merit (e.g., science value, cost, and risk) are considered repeatedly throughout the process and help guide the evolution and refinement of the set of architectures studied.

Some key attributes of the RMA approach are listed in Table 2, and major features of the RMA sessions are listed in Table 3. The JPL RMA process is discussed in more detail in the subsequent sections. Several illustrative examples of products are shown from a 2010 JPL RMA trade study of candidate mission concepts to Saturn's moon Enceladus for the National Research Council (NRC) "Solar System 2012" Planetary Science Decadal Survey [5] [6].

Table 2. Key attributes of the RMA approach

Exploring and preserving multiple options and trades	Retain multiple options throughout process and avoid driving to a "baseline" concept prematurely. Filter to a reasonable set of options for analysis but retain a diversity in the trade space.
Brainstorming for concept development	Use a mix of techniques to brainstorm new concepts at multiple stages in the process to open the trade space to diverse alternatives.
Appropriate level of detail	Be appropriately sparse. Identify and evaluate only the primary drivers in objectives, architectural options, key FOMs, and critical analyses. Focus on "tall tent poles" in the trade space.
Rapid results capture and disposition	Emphasize real-time results capture in sessions. Generate draft report products between sessions. Use "parking lots" to mitigate significant time sinks.
Feedback loops and iteration	New ideas can be introduced to the evaluation process at any phase.
Prioritization	Frequently reassess the primary study goals and time to complete. Filter and prioritize architecture options throughout the study.
Rapid turnaround	Timely response to customer needs. Maintain creative momentum of team in assessing the trade space.
Leveraging existing assets	Save significant start-up costs by leveraging existing participants, process, products, templates, tools, prior studies, facilities, and planning services. Avoid "reinventing the wheel" every study.

Table 3. Major features of the RMA sessions

Variety of mission concepts studied	Generation of dozens of trade space options followed by integrated mission assessments of 10 or more architectures (not just a point design)
Rapid turnaround	~1-3 weeks turnaround for group sessions, plus additional time for pre-study prep and post-study reporting
Participants	Typically 6-10 diverse architecture-level thinkers with the flexibility to quickly move in new directions based on emerging ideas and findings. People-focused process, not just a set of tools.
Customer active participation	Customer participates in real-time sessions to establish priorities and affect key decisions.
Pre-session work	Offline time for key participants with long-lead work (e.g., mission design)
Style of group sessions	Interactive group sessions with real-time work, typically 3-4 hours each. Activities include creative thinking, synthesis, and real-time first-order analyses.
Time for group concurrent sessions	Typically 4-8 concurrent small group sessions (study scope dependent). At least 3 days to allow offline work and percolation of ideas.
Work in between sessions	Offline assignments to generate and evolve products between sessions.

Table 4. Example science observation objectives and priorities

Nature of Enceladus; cryovolcanic activity	6	
Physical conditions at the plume source		4
Chemistry of the plume source		4
Presence of biological activity		1
Plume dynamics and mass loss rates		2
Origin of south polar surface features		2
Internal structure and chemistry of Enceladus	4	
Internal structure		3
Presence, physics, and chemistry of the ocean		4
Tidal dissipation rates and mechanisms		3
Chemical clues to Enceladus' origin and evolution		2
Geology of Enceladus	3	
Nature, origin and history of geological features		4
System Interaction	2	
Plasma and neutral clouds		4
E-ring		4
Modification of the surfaces of Enceladus and the other satellites		2
Other satellite science	2	
Nature of Titan's geological processes		4
Surfaces and interiors of Rhea, Dione, and Tethys		4
Preparation for follow-on missions	1	
Nature of potential landing sides		4

Group brainstorming is conducted early in the process (and again later) to "open the trade space" by generating new ideas and elements of the trade space that can be combined into mission concepts. The team works together to also identify important linkages between objectives and architectural options (e.g., what elements of the trade space can be used and combined to effectively achieve the high-priority science objectives, reduce risk, or reduce cost). Also, new or emerging technologies are identified and included in the trade space, but only where appropriate for enabling certain mission capabilities or mitigating specific cost or risk drivers (e.g., reducing launch costs or avoiding critical events in operations). Domain-specific preliminary analyses (e.g., additional trajectory analyses or compilation of technology data) are identified and dispositioned at this early stage.

The elements of the trade space are organized and assessed using various views. The trade space is decomposed into key trade dimensions (e.g., domain-specific trades such as trajectories, flight systems, instruments, critical functional trades, etc.) and various options within each trade. These trade options are organized using one of several various methods, depending on the focus of the study. One such construct is the RMA Key Trades Matrix, an example of which is shown in Fig. 3 (as a partial excerpt from a much larger full matrix). Trade space dimensions are shown in blue on the left. Options for each dimension are shown to the right. A green background implies that option was preferred, and a gray/faded background implies that option was (later) filtered or removed from further analysis in the study.

From the different organizational views, important dependencies and couplings between options and trades can be identified. This again allows the team to appropriately limit the quantity and combination of options to consider by focusing on the priority options and key drivers in the trade space. These key drivers are identified as "tall tent poles" (key challenges to meeting the science/technical objectives and requirements), particularly with respect to feasibility or cost/risk drivers. If necessary, the team can identify additional figures of merit (FOMs) to be assessed in the study. Additional domain-specific analyses or data collection can be conducted to resolve specific trades (or

Figure 3. Example partial excerpt from an RMA Key Trades Matrix

address feasibility issues) and facilitate in the next stage of filtering the trade space options.

5. Later Stages: Filter, Prioritize, and Evaluate the Trade Space

In the next major stage of the RMA process, the group focus is to filter and prioritize options in the trade space. Dozens of trade space elements are pruned, combined, and assembled into selected mission architectures. Each mission architecture concept is identified by a set of selections within the major trade dimensions (e.g., trajectory, flight systems, instruments, critical operational functions, etc.). These architecture selections enable the assessment of the mission-level figures of merit (e.g., science value, cost, and risk) later in the process. Candidate mission concepts are identified and then filtered by the group based on preliminary assessments of relative science benefits, cost, and risk impacts. The Facilitator/Architect and team strive to generate a diverse set of 10 or more mission architectures to proceed to the integrated analyses in the next stage. Additional brainstorming is often conducted on a more focused basis at this stage to generate potentially cost-effective and science-beneficial alternatives to fill in gaps or new opportunities in the trade space. Filtered options or ideas are kept in an effective "parking lot" to ensure capture for potential re-visit in the future. Fig. 4 shows an example of the architecture selections trade tree for the 2010 Enceladus RMA study. The architectures highlighted in green were selected to proceed to the following integrated assessment stage of the RMA process.

In the analysis and evaluation stage, the team conducts architecture-specific analyses and generates an integrated

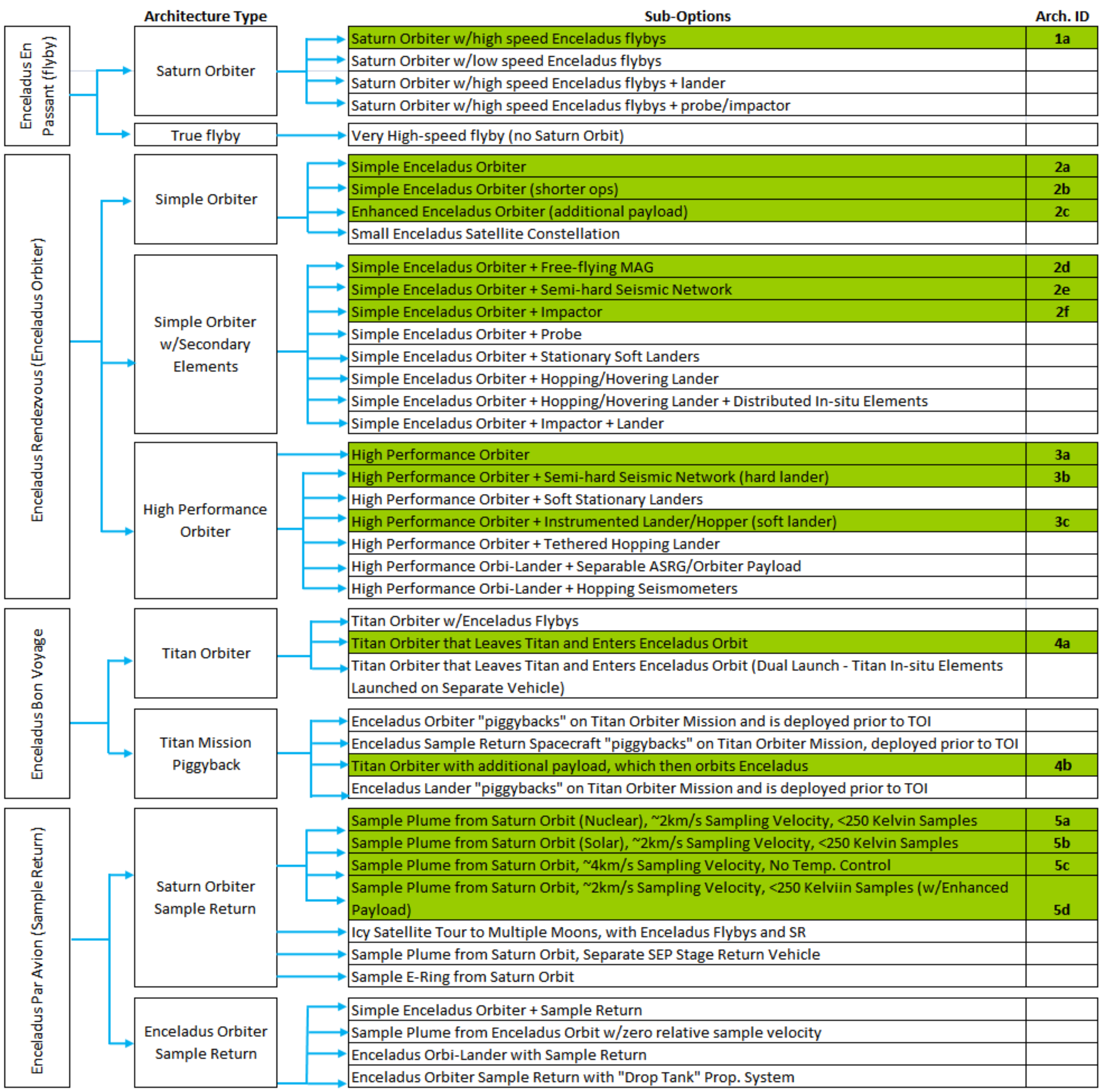

Figure 4. Example architecture selections trade tree

set of key figures of merit for the set of mission architectures. To enable rapid assessment across a diverse set of multiple architectures, analyses are conducted at a higher level (e.g., architectural or system level), rather than a more detailed point design level. Team members use parametric models, rapid first-order analysis techniques, and flight system analogies for their analyses and trades.

Science value is estimated via group assessments using the JPL RMA Science Value Matrix approach. The top-level science objectives are provided and grouped by the customer science team representatives and (if necessary) iterated after discussion with the RMA team. The science team associates each group with both a group priority weighting and a priority weighting for each objective within each group (each on a 0-10 scale). Mission architectures assessed in the RMA study are rated during the study by the science team on how well each of the architectures meets each science objective (again on a 0-10 scale). The ratings for each objective are weighted by their priorities, summed, and normalized for each architecture. The result is a set of quantitative relative (not absolute) science value rankings across the mission architectures studied. Because the process and results are iterated in the concurrent group sessions, the science team and RMA team can work together to reconcile discrepancies and refine the mission architectures to enhance mission science benefit. An example of the RMA Science Value Matrix is shown in Fig. 5.

Mission costs are estimated at the mission element and system level using parametric cost models, previous study data (where appropriate), and relevant flight system analogies. Appropriate reserves and modeling assumptions are applied consistently across the set of architectures. This approach allows rapid identification of cost drivers, identifies what missions fall within which cost classes, and enables relevant comparison across the mission architectures. Earlier in the process, the same tools and methods can also be used to perform quick, preliminary assessments of selected cost drivers to facilitate trade decisions. An example of a cost estimate comparison from an RMA study is shown in Fig. 6.

Both mission risks (operational risks that affect the ability to accomplish the mission objectives) and implementation risks (development risks that affect the consumption of cost, schedule, and performance resource reserves) are identified and assessed by the team members in NASA 5x5 (likelihood verses severity) risk matrices both during the sessions and offline. These risks are rated and aggregated for the various mission architectures, which are ranked lexicographically based upon these risks. An example product from this type of assessment of mission risks and implementation risks is shown in Fig. 7. The methods used for risk assessment in RMA are discussed in [7]. The team also strives to avoid any critical risks by modifying the

Science value for architectural options - Ratings approach: 0 = "Architecture does not address science objective", 10= "Architecture completely fulfills objective". "Completely" is subjective, particularly since very few areas of research are ever complete	Relative Category Science Value	Goal Science Value Relative in Category	Cassini (for reference)	Satum orbiter with E high speed flybys	Simple Enceladus Orbiter	Simple Enceladus Orbiter (shorter ops)	Enhanced Enceladus Orbiter	Simple Enceladus Orbiter (2a) + freeflying magnetometer	Simple Enceladus Orbiter (2a) + semi-hard seismic network	Simple Enceladus Orbiter (2a) + impactor	High Performance orbiter	High Performance orbiter + semi-hard seismic network	High Performance orbiter + instrumented lander/hopper	Titan-Enceladus Connection	Sample plume from Saturn orbit (nuclear), ~2 km/s sampling velocity, 250K samples	Sample plume from Saturn orbit (solar), ~2 km/s sampling velocity, 250K samples	Sample plume from Saturn orbit, ~4 km/s sampling velocity, no temperature control	5a with enhanced payload (2a w/no laser altimeter)
Study option designator			0	1a	2a	2b	2c	2d	2e	2f	3a	3b	3c	4a	5a	5b	5c	5d
Nature of Enceladus; cryovolcanic activity	6		2.8	4.7	5.3	4.9	6.5	5.2	5.6	5.6	6.9	7.2	7.7	6.4	6.9	6.9	5.9	7.7
Physical conditions at the plume source		4	2.5	4.8	4.7	4.5	5.9	4.7	5.2	5.5	6.2	6.3	6.8	5.9	6.3	6.3	4.9	7.5
Chemistry of the plume source		4	2.7	5.2	5.9	5.6	7.5	5.9	5.9	6.1	7.7	7.7	8.3	7.3	8.5	8.5	7.2	9.0
Presence of biological activity		1	0.0	2.4	3.0	2.8	5.3	3.0	3.0	3.9	5.1	5.1	6.4	4.3	8.3	8.3	6.7	8.3
Plume dynamics and mass loss rates		2	4.5	5.0	5.5	4.8	6.3	5.5	5.5	5.5	7.5	7.5	8.0	6.3	6.7	6.7	6.3	7.0
Origin of south polar surface features		2	3.0	4.3	6.0	5.3	6.7	5.7	7.0	6.0	7.3	8.3	9.0	6.7	4.3	4.3	4.3	6.0
Internal structure and chemistry of Enceladus	4		2.4	4.0	5.5	4.8	6.9	6.9	7.2	6.2	7.2	8.3	8.2	6.7	4.8	4.8	4.5	6.0
Internal structure		3	1.0	2.0	4.7	4.0	6.7	7.0	7.7	6.0	7.0	8.7	7.3	6.7	2.3	2.3	2.3	3.0
Presence, physics, and chemistry of the ocean		4	2.8	4.6	6.1	5.0	7.8	7.4	7.6	6.9	7.8	8.8	9.0	7.3	7.0	7.0	6.5	7.6
Tidal dissipation rates and mechanisms		3	3.0	4.3	5.3	5.0	6.0	6.7	7.3	5.7	6.3	8.0	7.7	5.7	2.3	2.3	2.3	5.0
Chemical clues to Enceladus' origin and evolution		2	2.9	5.2	5.6	5.4	6.8	5.9	5.6	5.6	7.4	7.4	8.5	6.9	7.8	7.8	7.1	8.8
Geology of Enceladus	3		3.0	4.7	5.7	5.0	7.3	5.7	6.7	6.3	7.7	8.7	9.0	7.0	3.0	3.0	3.0	4.7
Nature, origin and history of geological features		4	3.0	4.7	5.7	5.0	7.3	5.7	6.7	6.3	7.7	8.7	9.0	7.0	3.0	3.0	3.0	4.7
System Interaction	2		3.8	3.5	3.9	3.4	5.7	4.3	3.9	4.1	5.9	5.9	6.0	5.7	4.3	4.3	4.1	4.9
Plasma and neutral clouds		4	4.0	2.3	2.7	1.7	5.7	3.7	2.7	3.3	6.0	6.0	6.0	5.7	1.7	1.7	1.7	2.3
E-ring		4	4.0	4.7	4.7	4.7	5.3	4.7	4.7	4.5	5.5	5.5	5.5	5.3	7.0	7.0	6.7	7.0
satellites		2	3.0	3.7	4.7	4.3	6.3	4.7	5.0	4.8	6.3	6.5	6.8	6.7	4.3	4.3	4.0	5.7
Other satellite science	2		3.0	2.3	3.0	3.0	4.5	3.0	3.0	3.0	5.0	5.0	5.0	6.8	0.3	0.3	0.2	0.7
Nature of Titan's geological processes		4	3.0	1.3	1.3	1.3	3.3	1.3	1.3	1.3	4.7	4.7	4.7	8.7	0.0	0.0	0.0	0.0
Surfaces and interiors of Rhea, Dione, and Tethys		4	3.0	3.3	4.7	4.7	5.7	4.7	4.7	4.7	5.3	5.3	5.3	5.0	0.7	0.7	0.3	1.3
Preparation for follow-on missions	1		2.0	3.0	5.0	4.7	6.7	5.0	6.7	7.0	7.3	8.0	9.0	6.3	2.7	2.7	2.7	4.3
Nature of potential landing sides		4	2.0	3.0	5.0	4.7	6.7	5.0	6.7	7.0	7.3	8.0	9.0	6.3	2.7	2.7	2.7	4.3
Category value by Architecture, summed			17.0	22.2	28.3	25.7	37.6	30.0	33.0	32.2	39.9	43.0	44.9	39.0	22.0	22.0	20.3	28.2
Category Value-weighted, summed, normalized			0.85	1.21	1.49	1.35	1.93	1.59	1.71	1.64	2.04	2.20	2.28	1.96	1.36	1.36	1.23	1.66
Normalized to Reference Architecture			1.00	1.44	1.76	1.60	2.28	1.88	2.03	1.94	2.41	2.60	2.70	2.32	1.61	1.61	1.45	1.97
Sum					Key=	Low	Mid	High										

Figure 5. Example RMA Science Value Matrix

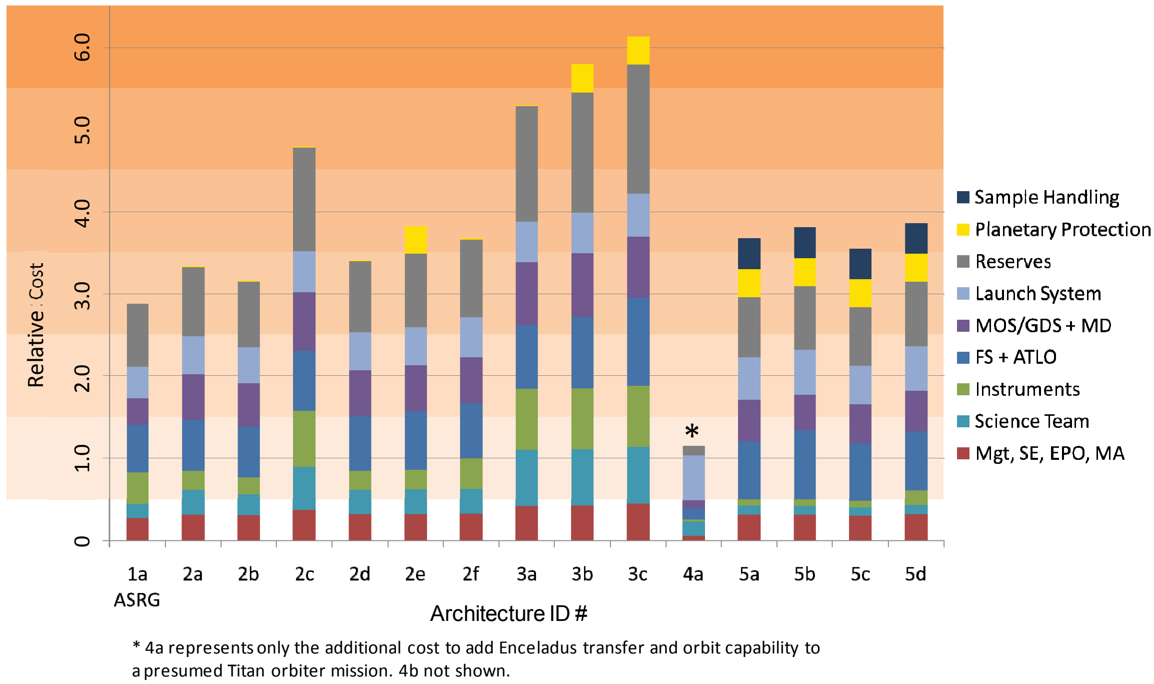

Figure 6. Example RMA multi-mission cost estimates and comparison (note the absolute costs were normalized to show relative costs here)

Mission Risk Architecture Ranking			
Arch	Red	Yellow	Green
2e	0	4	12
3b	0	4	12
3c	0	4	12
5a	0	3	9
5d	0	3	9
5b	0	3	8
5c	0	3	7
4a	0	2	8
2c	0	2	7
3a	0	2	7
2d	0	1	10
2f	0	1	9
2a	0	1	8
2b	0	1	8
1a	0	1	5

Implementation Risk Architecture Ranking			
Arch	Red	Yellow	Green
5a	0	5	6
5d	0	5	6
5b	0	4	6
3c	0	4	4
4a	0	4	2
5c	0	3	8
3b	0	3	5
2e	0	3	4
2c	0	2	4
3a	0	2	4
2d	0	2	3
2f	0	2	3
2a	0	2	3
2b	0	2	3
1a	0	1	4

Reduction in Mission Return/Consumption of Margin
Mission failure/Overrun
Significant
Moderate
Small to moderate
Minimal

Figure 7. Example results from RMA assessment of both mission risks and implementation risks

architectures to mitigate such risks upon identification. Thus, risk characterization early in the process (not left until the end) can be very important in forming an effective set of architectures.

Key figures of merit including science value, total mission cost, and risk are evaluated consistently across the set of architectures and compared in an integrated view. An example integrated assessment results view is shown in Fig.

8. In the final part of the RMA process, the best candidate architectures for further study in follow-on point designs are identified from the various mission concepts studied. This selection is made in conjunction with the customer/science lead representative(s) after results are reviewed and discussed in an RMA group session. This concurrent customer and team interaction ensures the integrated results reflect an appropriate accounting and balance of science benefits, cost-effectiveness, and acceptable risk. To

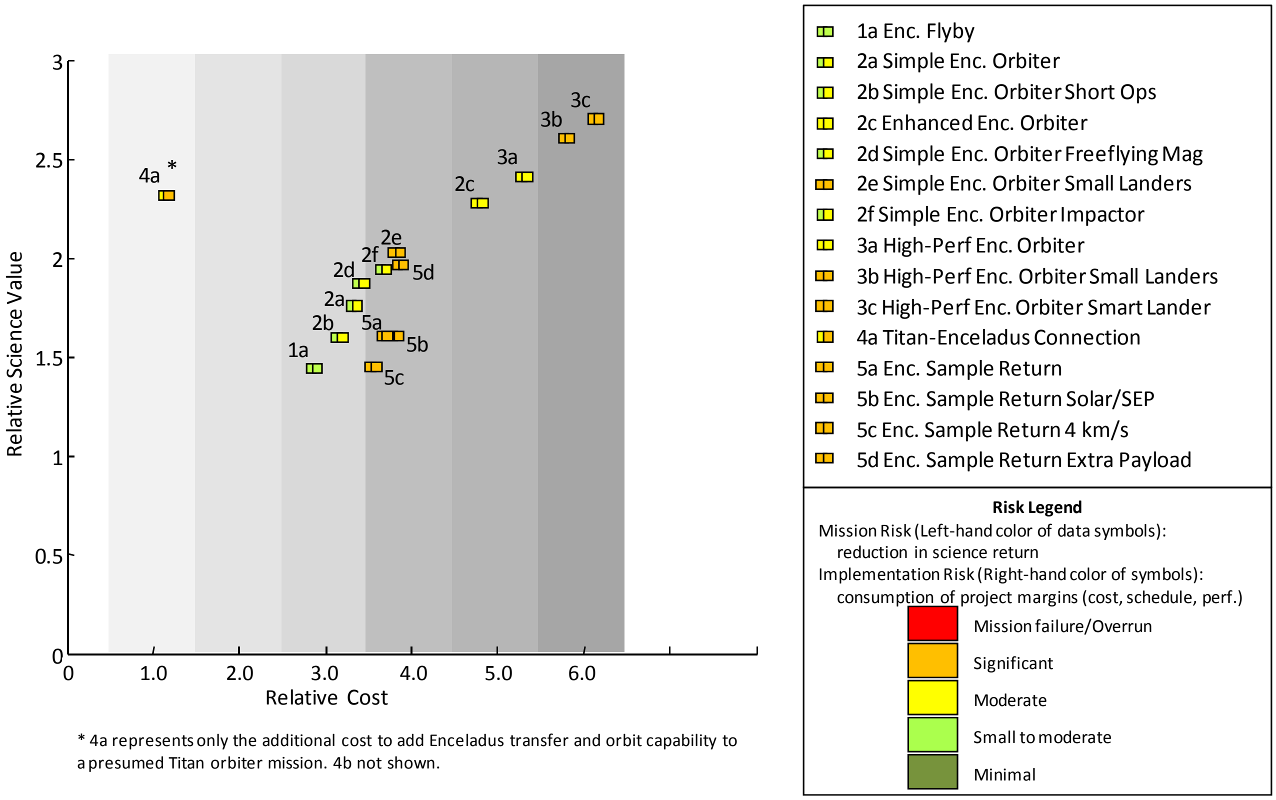

Figure 8. Example RMA integrated assessment results view showing relative science value, cost, and risk

complete the study, the key results and preliminary products are compiled into a final report or presentation. Products typically include (but are not limited to) the results from the trade space scoping and filtering, integrated assessments of the mission architectures (including science values, costs, and risks), mission trajectory designs and trades, rough mass estimates, operations concept timelines, and technology assessments. Again, it is important to note that analysis results are generated at a high level. E.g., mass estimates are provided at the flight system level, not the higher-precision subsystem or component level typical of a master equipment list (MEL) for a detailed point design study. Final products are reviewed with the customer and team to ensure consistency and quality.

6. RMA Results and Future Directions

Since its inception at JPL in 2007, the JPL RMA team and approach has conducted studies supporting various JPL and NASA program offices and external customers. Recent studies have also supported the ongoing National Research Council (NRC) "Solar System 2012" Planetary Science Decadal Survey [5] [6] [8]. RMA was developed to provide an alternative to higher-cost, comprehensive, early formulation phase architecture trade studies that run for several months. In this regard, RMA has demonstrated its utility as such an alternative by providing results in weeks, for significantly lower cost. Further, many of these early design teams are chartered to examine trade space options in a fairly narrow band around a presumed baseline design. RMA provides an additional capability that examines a much broader trade space exploration in an efficient, consistent, and effective manner. In some areas, the breadth and level of fidelity of the RMA studies is not at the level of some more comprehensive approaches, but that has shown to be an acceptable trade. In particular, the JPL RMA approach was found to be of significant interest to NASA and the NRC Planetary Science Decadal Survey. This interest resulted in a set of RMA-like, low concept maturity level trade space studies being commissioned for the Planetary Science Decadal Survey in late 2009 through 2010. There is ongoing significant interest and support at JPL and NASA to conduct RMA-like mission architectural trade space studies as a precursor to point designs for a variety of early mission studies.

If definition of the mission, spacecraft, and instrument concept is not well-established prior to initiating a point design study, this can result in an inefficient design process, possibly entailing multiple dead-ends or consideration of several alternative point designs in a more costly serial design process with a large team. RMA provides a more efficient approach than running multiple point design studies without consideration of architecture level trades a priori. RMA thus helps to avoid the costs associated with mistakes in architectural choices stemming from prematurely selecting a baseline without the benefit of a trade analysis. In addition, creative exploration of a broader trade space via RMA often uncovers promising concepts that might have otherwise been overlooked.

RMA studies use hybrid parametric and analogy-based modeling approaches that approximate the more detailed Team X point design team models. Recent studies for the Planetary Science Decadal Survey have shown the results of these models to be within reasonable ranges (~20%) when compared to the Team X point design results.

RMA is now offered within the set of evolved "Team X" banner of early mission formulation services at JPL. Most of the RMA studies to-date (and the methods described in this paper) have been the type that examine a broad trade space of mission architectures, particularly for planetary exploration. New and evolving RMA study types are being tailored to also support studies with different scopes, including focused architecture-specific trade studies, quick feasibility assessments, and multi-mission technology assessments.

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REFERENCES

[1] T.R. Spilker, R.C. Moeller, C.S. Borden, W.D. Smythe, R.E. Lock, J.O. Elliott, J.A. Wertz, and N.J. Strange. "Analysis of Architectures for the Scientific Exploration of Enceladus," IEEEAC paper #1644, 2009 IEEE Aerospace Conference, Big Sky, MT, USA, March 2009.

[2] M. Kordon, and K. Warfield, "Addressing Concept Maturity in the Early Formulation of Unmanned Spacecraft," Proceedings of the 4th International Workshop on System and Concurrent Engineering for Space Applications (SECESA 2010), Lausanne, Switzerland, October 13-15, 2010.

[3] B. Sherwood, M. Adler, R. Wheeler, "The New Team X: Concurrent Engineering Advancement at JPL," Presentation at the 58th International Astronautical Congress, Hyderabad, India, September 24-28, 2007.

[4] S. Wall, "Reinventing the Design Process: Teams and Models," IAF, Specialist Symposium: Novel Concepts for Smaller, Faster & Better Space Missions, Redondo Beach, CA, USA, 1999.

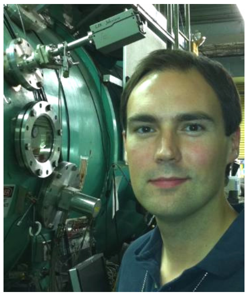
[5] J. Spencer, C. Niebur, M. Adler, R. Moeller, C. Borden, W. Smythe, T. Spilker, et al, "Planetary Science Decadal Survey JPL Rapid Mission Architecture (RMA) Enceladus Study Final Report," NASA Mission Concept Study Report, April 2010.

[6] M. Adler, J. Spencer, R. C. Moeller, C. S. Borden, W. D. Smythe, R. F. Shotwell, B. F. Cole, T. R. Spilker, N. J. Strange, A. E. Petropoulos, D. Chattopadhyay, J. Ervin, E. Deems, and P. Tsou, "Rapid Mission Architecture Trade Study of Enceladus Mission Concepts," 2011 IEEE Aerospace Conference, Big Sky, MT, USA, March 2011, unpublished (submitted for publication).

[7] J. Hihn, D. Chattopadhyay, R. Shishko, "Risk Identification and Visualization in a Concurrent Engineering Team Environment," Proceedings of the ISPA/SCEA 2010 Joint International Conference, San Diego, CA, USA, June 8-11, 2010.

[8] M. Marley, L. Dudzinski, T. Spilker, R. Moeller, C. Borden, W. Smythe, et al, "Planetary Science Decadal Survey JPL Rapid Mission Architecture Neptune-Triton-KBO Study Final Report," NASA Mission Concept Study Report, February 2010.

BIOGRAPHY



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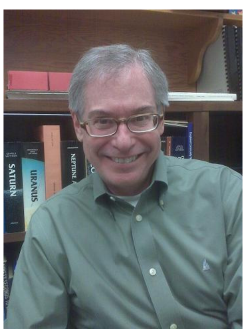

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